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CARDEROCKDIV-93/006 Structural Evaluation of Diagonal Riders for the USS Constitution

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Naval Surface Warfare Center**

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Joint Technical Report

**Structural Evaluation of Diagonal
Riders for the USS *Constitution***

by
Roger Hoffman
Kevin Lynaugh

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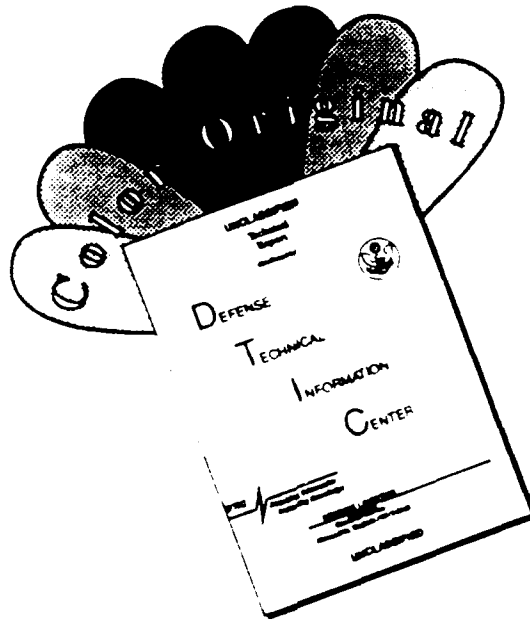


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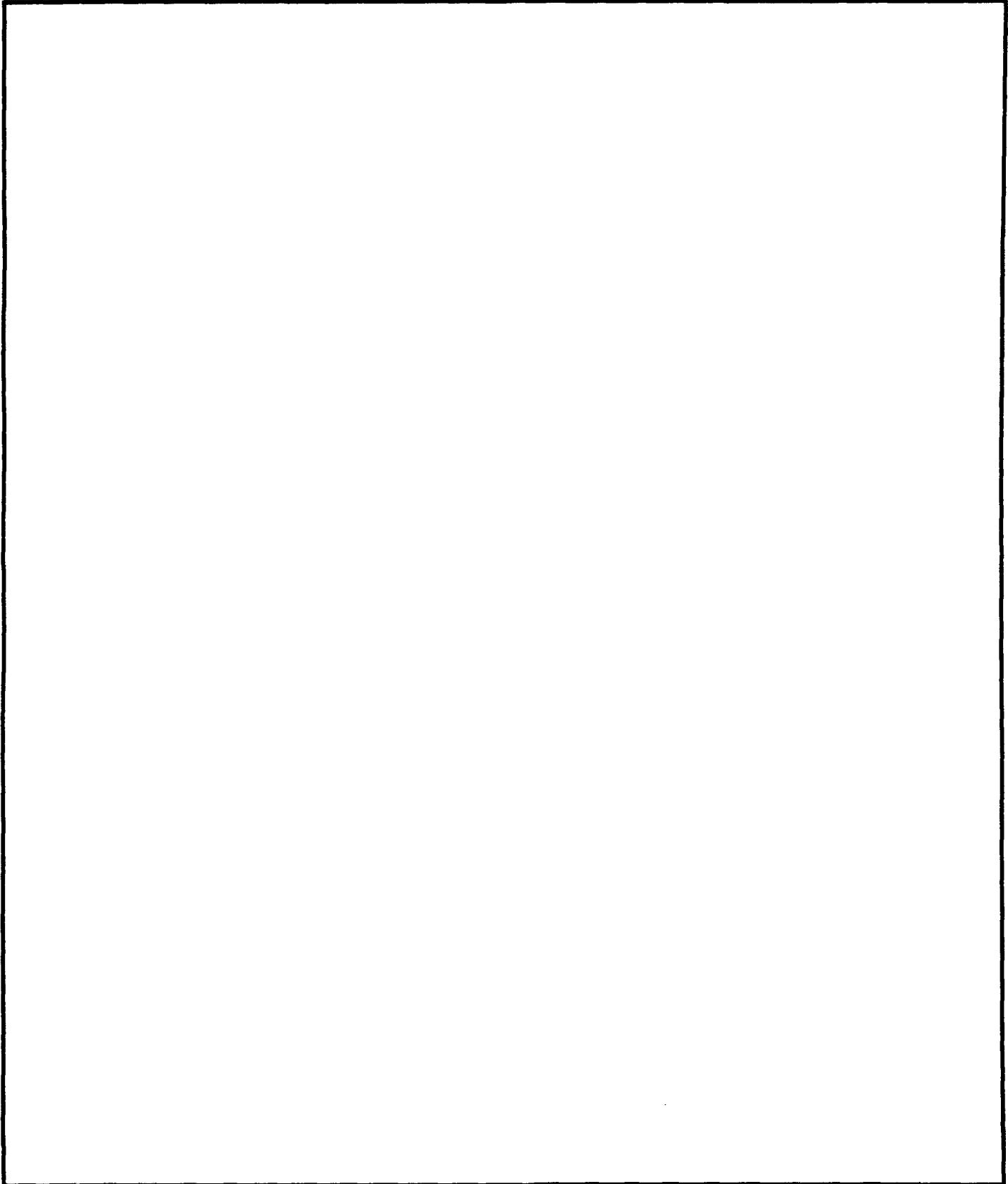


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ABSTRACT

A study of the addition of diagonal riders to the USS CONSTITUTION has been completed. The function of the proposed riders is to reduce the hogging rate of the ship. Installation of diagonal riders will also help to restore the ship to its original as-built condition of 1797. The goals of the study were to estimate any hogging rate reduction produced by the riders and to develop an improved understanding of the mechanisms that cause hogging in wooden ships. Since hog is caused predominately by bending loads, the effect of the riders on the bending response of the ship was investigated and both analytical and experimental methods were employed. Within the scope and assumptions made in the study, the riders were found to have little effect on the bending response of the CONSTITUTION.

Deformation of pinned connections contributes to the progression of hog in a wooden ship. This deformation is due to bearing stresses, pin deformation and pin corrosion. The riders may contribute to reducing the hogging rate of the CONSTITUTION, particularly in the short term, by virtue of the tightly fastened joints between the riders and the hull. The analytical and experimental evaluations of the proposed riders, however, did not account for these effects.

A recommendation to perform a weight survey of the CONSTITUTION is made. A more uniform distribution of weights on the ship could reduce the hogging rate. In addition, the installation of data acquisition systems both for short-term and long term structural monitoring is suggested.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

Over the past several years, the Naval Historic Detachment has reviewed numerous proposed hull strengthening methods for CONSTITUTION. These proposals were solicited in

an attempt to procure an effective, contemporary system which would reinforce the CONSTITUTION's hull in order to arrest its natural tendency to hog. A brief synopsis of these proposed solutions are listed to provide an idea of their breadth: (1) Buoyancy or flotation tanks at the bow and stern to offset the dead weight in those areas; (2) Metal double-diagonal strapping similar to that used on wooden ships during the latter part of the nineteenth century; (3) A thin metal/composite shell between the frames and inner ceiling planking; (4) A composite diagonal truss frame similar to designer Joshua Humphreys 1797 original wooden diagonal riders; (5) Metal diagonal strapping of the keel with I-beams above the keel; and (6) Permanent dry dock of the ship in a similar fashion to HMS Victory.

Although the previously proposed strengthening systems could possibly solve the hogging problem, they all infringe on the fundamental historic value of the ship and violate the historic preservation plan. Consequently, the Detachment abandoned the desire for a contemporary solution in favor of a historically accurate solution. A strengthening system used in the early 1800's employed diagonal stiffeners referred to as riders. Historic documentation exists^{1,2} providing evidence that diagonal riders may have been installed in CONSTITUTION during her construction.

The Carderock Division, Naval Surface Warfare Center (CDNSWC) was tasked to provide the Detachment with a structural evaluation of the diagonal rider stiffening system proposed for the USS CONSTITUTION. The rider dimensions and locations in the ship are described in References 1 and 2. A schematic drawing of the proposed riders are shown in Figure 1.

NAVAL ARCHITECTURE BACKGROUND

The USS CONSTITUTION is a skeletal structure constructed from heavy wooden timbers held together by pinned connections. The main components of the ship are the keel, frames, hull planking, decking, deck beams, and caulking. The wooden structure consists of native live oak (frames, knees, hooks), white oak (keel, beams, planking), douglas fir (masts, spars, beams), red cedar (decking) and pitch pine (planking, decking). The caulking consists of cotton and oakum fibers forced between the planks to produce a water-tight seal. The pin connections are made of iron, copper and wood (locust) trenails. The outside hull from the keel to the 24 foot waterline is covered in $\frac{1}{8}$ -inch thick copper sheathing to protect the wood from marine parasites. The skeletal structure of the ship must support its own weight, oppose its buoyancy force and resist environmental degradation. In addition, the ship is subject to transient environmental forces such as wind, waves, heat, humidity, bacteria, fungi, and insects.

HOG

Hog is a nautical term used for hundreds of years to describe the shape of wooden ships. The term provides a mental picture of a ship whose shape resembles the appearance of the arched back of a hog or a pig. The term quickly conveys the longitudinal shape of the ship to those concerned with its structural integrity.

Hog is measured from a designed flat keel line up to the highest vertical point of the distorted keel. An illustration of this measurement is shown in Figure 2. The hog in a wooden ship produces a corresponding horizontal movement of the ship structure due to the relative sliding of hull planks. Figure 3 illustrates the relationship between vertical and horizontal

movement for stacked planks that are free to slide relative to each another. If the stack is bent by applying a downward load at each end of the stack and an upward load in the middle of the stack, the planks will bend as well as slide past each other. For example, if the planks are loaded to produce a vertical stack displacement of 2.5 feet, the corresponding horizontal displacement of the top planks will be approximately 0.115 feet.

The stacked plank analogy illustrates that hog is manifested as vertical as well as horizontal deformation of the skeletal ship structure. Consequently, hog in a wooden ship can be minimized by increasing the longitudinal bending stiffness of the skeleton as well as by restraining the horizontal movement of the structure to within a tight tolerance.

The consequences of hog in a wooden ship can be profound and possibly catastrophic. As the vertical deflection of a ship's keel increases with time, the ship's planks slide past each other, the caulking and pinned connections loosen or fail, leaks develop, and the ship's structural integrity becomes questionable. Consequently, drydocking, surveying, and possibly rebuilding of the skeleton structure may become necessary.

Unfortunately, past documentation which describes the critical magnitude of hog-induced deflection for wooden ships such as CONSTITUTION is lacking. The CONSTITUTION was drydocked with approximately 13 inches of hog in her keel. Hopefully, the proposed structural improvements will reduce the rate of hog in the ship so that the critical hog-induced deflection is never reached.

SHIP LOADS

The two primary loads on a ship hull are the buoyancy force acting upward and the

weight force acting downward. A mismatch in the distribution of these two loads creates a bending moment in the hull. This mismatch primarily is due to the shape of the hull and the distribution of weight in the ship. If the ship were a rectangular block of wood with a weight distribution that matched the buoyancy distribution on the block, no bending moment would be created. A ship, however, requires a shaped bow and stern. Consequently, the buoyancy provided by the bow and stern does not balance the weight in these areas. Therefore, the ship is loaded by forces that eventually cause hogging.

The buoyancy curve is calculated by summing the volume of water displaced by the ship's hull at designated locations known as stations and multiplying the sum by the weight of water per cubic foot. Similarly, the weight curve is calculated by summing the weight of the ship at these stations. The ship weight includes the weight of the wood, fastenings, masts, anchors, and cargo. This calculation is tedious and often requires several iterations in order to converge on the actual distribution. Typical weight and buoyancy distributions are shown in Figure 4.

The summation of the buoyancy and weight curves produces the loading curve. For commercial wooden cargo ships, load curves typically are generated at three drafts in order to provide the designer with a trend by which to minimize the load curve and, subsequently, the moments acting on the hull. These curves, shown in Figure 5, illustrates the net downward forces at the bow and stern of the ship and the net upward force amidships. The ship structure experiences this longitudinal force distribution as tension in the shear strakes (top of the ship) and as compression at the keel (bottom of the ship). From the load curve, the shear and the bending moment curve are derived. Typical shear and bending moment curves are shown in Figure 6.

The ship's scantlings are determined using the bending moment curve. For analytical purposes, the ship's bending response is assumed as one-dimensional and classical beam theory is used to determine scantlings based on the maximum bending moment. Typically, the maximum bending moment is computed both for both still-water and seaway conditions. For the purposes of this study, the CONSTITUTION was assumed to be subjected to still-water forces for the following reasons. First, the ship is moored in a protected berth. Secondly, the maximum bending moment for a ship in a seaway is short in duration, typically less than a minute. Thirdly, the progression of hog is the result of hull forces acting over a long period of time, typically years.

Analysis of ship bending using beam theory is a currently accepted practice for steel ships. The bending of a steel ship is analogous to the bending of a homogeneous beam because steel ships are constructed using welded joints. Welded joints do not allow relative motion between connected members. The USS CONSTITUTION, however, can not be accurately analyzed with beam theory alone. The skeletal structure of the CONSTITUTION contains numerous pinned joints which allow relative motion between connected members. Consequently, the CONSTITUTION does not bend as a homogeneous structure. Indeed, computation of the CONSTITUTION's deflection using beam theory, as shown in Reference 3, predicts a maximum vertical ship deflection of 0.25 inches due to the bending moment produced by the buoyancy/weight mismatch. The actual vertical ship deflection is approximately 13 inches. The discrepancy in predicted versus actual ship deflection can be attributed to the deformation of pinned connections due to bearing stresses, pin deformation and pin corrosion as well as to environmental degradation of the mechanical properties of the wood and caulking.

STRUCTURAL ANALYSIS

The objective of the structural analysis of the proposed diagonal rider system was to provide an analytically-based estimate of the contribution of diagonal riders to increasing the hogging resistance of the USS CONSTITUTION. Currently, no documentation exists which describes the mechanism by which diagonal riders stiffen a ship such as the CONSTITUTION. Consequently, structural analyses were completed to determine both the riders' stiffening mechanism and the riders' contribution to ship's stiffness.

Prior to initiating structural analysis of the rider stiffening system, a review of previous structural calculations^{3,4} for CONSTITUTION was completed. The purpose of the review was to collect engineering data required for the present task and to confirm the magnitude of ship deflection due to hogging.

An accurate determination of ship deflection is paramount to the present investigation, since any benefit provided by the riders directly influences the deflection. The CONSTITUTION analysis presented in Ref. 3 was completed using a standard naval architecture analysis⁵. This analysis assumes that the still-water response of a ship to the bending moment created by a weight/buoyancy mismatch is analogous to simple beam bending. The analysis, however, is not suitable for use in determining the influence of the diagonal riders on the still-water response of CONSTITUTION since the ship's bending response can not be determined with homogeneous beam theory. In addition, the analysis assumes ship response is one-dimensional (longitudinal). The riders may influence both the athwartship and longitudinal response of the ship. Consequently, the finite element method was employed for the current investigation to overcome these shortcomings.

The tools used for the investigation included PATRAN, a FEA pre- and post-processor⁶, and ABAQUS, a general-purpose finite element code⁷. PATRAN was executed on a Silicon Graphics Iris 4D/35 workstation and ABAQUS was executed on a Cray XMP-24 supercomputer.

BEAM FINITE ELEMENT ANALYSIS

The first step in analyzing the rider stiffening system was to establish a baseline for ship deflection using finite element analysis (FEA). Although the maximum ship deflection due to hogging was computed in Reference 3, computation of a maximum ship deflection using FEA was necessary since the previous neglected transverse shear deformation. Consequently, an ABAQUS beam analysis was completed.

Since beam structural analysis is one-dimensional, a one-dimensional geometric representation (lines) of the ship was generated using PATRAN. For the purpose of this investigation, CONSTITUTION was assumed to possess both longitudinal and athwartship symmetry. Consequently, only one-half of the ship length (10 stations) was included in the geometric representation.

A finite element representation of the ship was generated by discretizing the geometric representation with B32 beam elements. B32 beam elements have three nodes with six degree of freedom per node ($\{u, v, w, \theta_x, \theta_y, \theta_z\}$), quadratic displacement interpolation and transverse shear deformation. In "English", B32 elements are the most accurate beam elements in the ABAQUS element library. The beam finite element representation is shown in Figure 7.

The elements of the finite element representation were assigned the equivalent Young's

modulus reported in Reference 3. Since no equivalent Poisson's Ratio was reported in Reference 3, a value of 0.3 was assumed and assigned to the elements. Although wood is an orthotropic material and ABAQUS provides the capability for orthotropic material representation, the use of an isotropic material representation was warranted considering the rough order of magnitude approach used in this investigation. The representation was constrained with displacement boundary conditions to simulate a simple support at the FP ($\{u, v, \theta_z\} = 0$) and a symmetry support at station 10 ($\{w, \theta_x, \theta_y\} = 0$). Although Reference 3 lists the net loads on the ship, a uniformly distributed load which approximated the actual loading was applied to the model to facilitate interpretation of results.

An ABAQUS analysis of the CONSTITUTION beam representation was completed. Figure 8 shows the predicted longitudinal distribution of vertical ship deflection. Note that the maximum deflection computed by the ABAQUS analysis is greater than the previously computed maximum deflection. The disparity in predicted ship deflection is due to the different beam theories employed; ABAQUS beam elements were formulated using Timoshenko Beam Theory⁸, which accounts for transverse shear deformation, and analytical methods previously described were formulated using Euler-Bernoulli Beam Theory⁹, which neglects transverse shear deformation.

Figure 9 shows a comparison of the longitudinal distribution of bending moment in the ship as predicted by ABAQUS analysis and by naval architecture analysis. The relatively close agreement between distributions demonstrates that the uniformly distributed load used in the analysis was a good approximation of the net ship loads.

SHELL FINITE ELEMENT ANALYSIS I

Once the baseline ship deflection had been accurately determined, a more detailed finite element representation of the CONSTITUTION's hull and diagonal riders was developed. A "notional" hull was created which possessed virtually the same cross-sectional moment of inertia as the cross-section of the CONSTITUTION at Station 10 but without the structural details of the actual cross-section. The purpose of a notional hull representation was to avoid expending time developing a detailed representation and to expedite the investigation of multiple rider system configurations since modifications to the representation could be easily made.

An isosceles trapezoid was chosen as the cross-sectional shape of the notional hull. In order to derive the required dimensions of the trapezoidal cross-section, the cross-section was assumed to possess a uniform wall thickness of 2.0 ft. The appropriate dimensions of the trapezoid, therefore, could then be manipulated in order to achieve a sectional moment of inertia which approximated the sectional moment of inertia of the CONSTITUTION at Station 10.

Once the notional hull cross-section was determined, a notional hull geometry was generated using PATRAN. Assuming both longitudinal and athwartship symmetry, only one-half of the ship length and one-half of the cross-section were represented. The hull geometry, which consisted of two-dimensional entities representing the hull (patches) and one-dimensional entities representing the riders (lines), is shown in Figure 10.

Two shell finite element representations of the notional hull were generated. An unstiffened hull representation was generated by discretizing the hull patches with S8R shell elements. ABAQUS S8R shell elements have eight nodes with six degrees of freedom per node, quadratic displacement interpolation and transverse shear deformation. The mechanical

properties reported in Reference 3 were assigned to the hull elements. Note that these material properties are "notional" and do not represent actual properties of any specific type of wood. A simply-supported displacement boundary condition ($\{u,v\}=0$) was applied to those node located on the plane of the representation corresponding to the forward perpendicular. A symmetry displacement boundary condition ($\{w,\theta_x,\theta_y\}=0$) was applied to those nodes located on the longitudinal symmetry plane of the representation located at Station 10. In addition, a second symmetry boundary condition ($\{u,\theta_y,\theta_z\}=0$) was applied to those nodes located on the athwartship symmetry plane. A uniformly distributed pressure load was applied to the representation. The magnitude of the pressure load was chosen so that the net vertical reaction force at the simple support would equal the vertical reaction force at the simple support in the beam analysis.

A stiffened hull representation was generated by discretizing the rider lines with B32 beam elements and the hull patches with S8R shell elements. Note that including six riders in the stiffened hull representation corresponded to the case of 12 riders per side (port/starboard). Twelve riders per side was the "stiffest" case under consideration. The orientations and cross-section of the beams followed the conventions described by Humphreys in Reference 2. The material properties, boundary conditions, and loading that were applied to the unstiffened representation were applied to the stiffened representation. The stiffened hull representation is shown in Figure 11. Although the location of the rider beam elements coincided with the location of the hull shell elements, the bending axis of the beam elements mathematically are offset from the midplane of the shell elements in order to approximate the actual configuration.

An ABAQUS analysis was completed for each notional hull representation. The

contribution of the riders to the stiffness of the ship was determined by comparing the maximum vertical displacement of the stiffened hull representation with the maximum vertical displacement of the unstiffened hull representation. The comparison was performed for those nodes located on the longitudinal symmetry plane of the representation (Station 10). Unfortunately, the deflection comparison revealed that the riders produced less than a 1.0% increase in the bending stiffness of the ship.

The original intent of the riders was to transmit hull hogging forces into the keel. The lack of cross-sectional deformation of the hull, as predicted by ABAQUS analyses of the notional hull representations, leads one to believe that load transfer from the hull to the keel is not the mechanism by which diagonal riders stiffen a ship. Therefore, a tentative conclusion can be reached that the riders will not improve the resistance of the CONSTITUTION to longitudinal hull bending.

SHELL FINITE ELEMENT ANALYSIS II

The conclusions deduced from the results of the first shell analyses could be disputed due to the absence of curvature and structural details in the notional hull geometry. Consequently, a second set of shell representations were generated in order to investigate the performance of diagonal riders in a more realistic hull representation. Note that the effort to create hull representations whose maximum vertical deflection equalled the maximum vertical deflection computed by the ABAQUS beam analysis was abandoned at this point in favor of creating more realistic representations of the CONSTITUTION.

The improved geometric representation of the CONSTITUTION included a curved hull,

a keel, and spar, gun and berth decks. The hull contour was generated using centerline offsets from the USS CONSTELLATION. Although these offsets do not exactly correspond to the CONSTITUTION offsets, the resulting contour sufficiently captured the basic form of the CONSTITUTION hull. In order to facilitate geometry generation, both the keel and the diagonal riders were represented with one-dimensional geometric entities (lines). The decks and hull, however, were represented as two-dimensional geometric entities (patches). The improved geometric representation of the hull is shown in Figure 12.

Two shell finite element representations of the CONSTITUTION were created. An unstiffened representation was generated by discretizing the hull and deck patches with S8R shell elements and the keel lines with B32 beam elements. A stiffened representation was generated by discretizing the rider lines with B32 beam elements in addition to discretization performed for the unstiffened representation. For both representations, isotropic material properties, simply-supported and symmetry displacement boundary conditions, and distributed loading were employed in the exact manner as in the previous shell representations.

The contribution of the riders to stiffening the ship was determined using the procedure followed for the previous shell analysis. Unfortunately, the deflection comparison again revealed that the riders produce less than a 1.0% increase in the bending stiffness of the ship. Therefore, one can conclude with increased confidence that the diagonal rider stiffening system will not improve the resistance of the CONSTITUTION to longitudinal bending.

SOLID FINITE ELEMENT ANALYSIS

The conclusions deduced from the results of the improved shell analysis of the

CONSTITUTION could be disputed due to the representation of the hull and decks as shells and the keel and diagonal riders as beams. Consequently, a three-dimensional CONSTITUTION hull representation was created in order to investigate the effect of finite element modeling strategy on the prediction of hull deformation.

The unstiffened geometric representation of the CONSTITUTION included the curved hull, the keel, keelsons and sister keelsons, and the spar, gun and berth decks. The hull contour was created using the CONSTELLATION offsets and the complete geometric representation was generated assuming longitudinal and athwartship symmetry. Note that the hull, keel members and the decks were represented as three-dimensional geometric entities (hyperpatches). The geometric representation is shown in Figure 13.

An unstiffened finite element representation of the CONSTITUTION was generated by discretizing the entire geometric representation with C3D20R solid elements. C3D20R elements are twenty node, three degrees of freedom per node ($\{u,v,w\}$), quadratic interpolation elements. Note that solid elements intrinsically include transverse shear deformation since they represent the actual thickness of the structure. A simply-supported displacement boundary condition ($\{u,v\}=0$) was applied to those node located on the plane corresponding to the FP. A symmetry displacement boundary condition ($\{w\}=0$) was applied to those nodes located on the longitudinal symmetry plane of the representation (Station 10). A second symmetry displacement boundary condition ($\{u\}=0$) was applied to those nodes located on the athwartship symmetry plane. A uniformly distributed pressure load was applied to the those elements representing the keel. The magnitude of the pressure load was chosen so that the net vertical force applied to the keel equaled the net vertical force applied to the keel in the improved shell analysis.

Figure 14 shows the predicted deformed shape of the solid hull representation. As with the results of both of the shell analyses, the lack of cross-sectional deformation of the solid hull representation leads one to conclude that the riders are ineffective in increasing the ship's longitudinal bending stiffness. Unfortunately, a time constraint prevented the creation of a stiffened hull representation.

Preliminary structural analyses were completed to investigate the effect of a diagonal rider stiffening system on the bending response of the USS CONSTITUTION. The approach of the investigation was to use finite element analysis to determine the stiffness increase provided by diagonal riders by comparing the vertical deflections of stiffened versus unstiffened hull representations when subjected to bending loads. The investigation was carried out using multiple finite element representations of the hull and diagonal riders. The representations were developed with increasing detail, from one-dimensional to fully three-dimensional in order to accurately determine the riders' effect on the bending response of the hull. Unfortunately, all of the analyses predicted that the riders provide an insignificant increase in the bending stiffness of the ship. The results of this investigation, however, were influenced by the numerous assumptions made in creating and analyzing the finite element representations of the ship hull and riders. The merit of a diagonal rider stiffening system for CONSTITUTION can not be judged by analytical results alone. Therefore, an experimental investigation of the diagonal rider system was performed.

MODEL TESTING

An experimental evaluation of the effect of diagonal riders and other proposed structural

members on the bending response of the CONSTITUTION was completed jointly by NHC and CDNSWC. The purpose of the evaluation was to experimentally determine the contribution of the diagonal riders and other members to increasing the CONSTITUTION's resistance to hogging. A $1/16$ -scale wooden model used in a previous investigation of the ship (Reference 4) was used for the experiment.

The model had been fabricated using similar construction techniques and materials used for CONSTITUTION. Unfortunately, the model represents only a portion of the actual ship structure. Although most of the frames are represented and ribbands are attached to give the hull form, hull planking, deck beams, and decks are not represented. Approximately 30% of the model consists of close frame spacing representative of the spacing on the CONSTITUTION.

In order to determine the contribution of the diagonal riders and other members to increasing the CONSTITUTION's resistance to hogging, NHC adopted the simple loading scheme described in Reference 4. Four-point bending was applied to the model using the following procedure. The model was inverted and supported on two sawhorses. The sawhorses were positioned in order to support the model at locations approximately corresponding to the locations of maximum vertical shear in the ship. Load was applied to the model by suspending a load platform from the keel using steel slings at Stations $8\frac{1}{2}$ and $10\frac{1}{2}$. The location of load application was chosen so that the maximum bending moment produced in the model occurred at approximately the same location as it does in the ship. The model configured for testing is shown in Figure 15.

The response of the model to four-point bending was determined by measuring vertical keel deflections at twenty longitudinal stations. A Kevlar string was stretched the length of the

keel and attached to the model at Stations 1 and 20 as shown in Figure 16. The purpose of the string was to establish a reference line from which vertical keel deflection could be measured.

NHC completed a series of eight load tests on the $1/16$ -scale wooden model. The first test was completed on the model in an "as-is" condition to determine the stiffness of the "empty" model, where "empty" refers to a lack of any structural members such as decks, deck beams, etc. The model was prepared for loading and subjected to a maximum load of 678 pounds. Excessive keel deflection prevented the application of additional load and the test was halted.

The second test consisted of loading a "full" model which was reinforced with numerous structural members as shown in Figure 17. The following scaled components were installed in the model:

- (1) Keelson;
- (2) Berth deck thick strakes, stem and transom knees;
- (3) Berth deck and gun deck beams;
- (4) Three sets of diagonal riders (12 total, six port/starboard);
- (5) Two sets of transom riders.

A maximum load of 2288 pounds was applied to the model. A comparison of the bending moment in the model produced by the maximum test load and the bending moment in the CONSTITUTION produced by the weight/buoyancy mismatch is shown in Figure 18. Note that bending moment in the model was scaled to match the scale of the CONSTITUTION. The comparison illustrates that the simple four-point bending scheme used for the model tests produced a fairly accurate reproduction of the bending moment experienced by the actual ship.

The remaining six tests were performed with the model in the following configurations and with the following maximum loads:

- Test 3: Thick strakes removed (2288 lbs.);
Test 4: First set of diagonal riders removed (2288 lbs.);

Test 5: Transom riders removed (2288 lbs.);
Test 6: Second set of diagonal riders removed (1556 lbs.);
Test 7: Third set of diagonal riders removed (1030 lbs.);
Test 8: Deck beams and knees removed (634 lbs.).

Note that the model configuration progressed from a "full" model containing all of the proposed structural members (Test 2) to an "empty" model devoid of structural members (Test 8). Keel deflections recorded in each test, scaled to the lowest test load, are shown in Figure 19. Examination of the keel deflections reveals the large contribution of the diagonal riders to the stiffness of the model. The keel deflections progressively increased as each set of diagonals was removed. The largest increase occurred when the third set of riders were removed. Fortunately, this trend agrees with the intuitive thought that the rider set closest to amidships, the third set, should contribute the greatest amount of stiffness to the model since the maximum bending moment and, therefore, the largest deflection occurs amidships.

CDNSWC used deflection data from the scale model tests to estimate the bending stiffness of the diagonal riders and the other structural members used to reinforce the model. If one assumes the model's bending response is one-dimensional (longitudinal), then the model can be analyzed using classical beam theory. A closed-form relationship exists for a beam loaded in four-point bending which relates the beam deflection to the maximum bending moment, Young's modulus (E), moment of inertia (I), length, and load application points¹⁰. Since the model's deflection, maximum moment, length, and load application points were known, the relationship was solved for EI , the effective bending stiffness of the model. Therefore, effective bending stiffnesses of the model with various structural components installed were computed. This procedure assumes that the increases in experimentally observed keel deflections directly resulted from bending stiffness decreases in the model due to the removal of structural members such as

diagonal riders. Therefore, the decrease in model bending stiffness was assumed to equal the bending stiffness of the structural component(s) removed from the model. Note that the bending stiffness of each structural component was derived based on the decrease of the model's bending stiffness at Station 10.

The percent decrease in bending stiffness of the model due to component removal, relative to the "full" model, is shown in Figure 20. The removal of the diagonal riders from the model decreased the model stiffness far greater than the removal of the other structural members. Conversely, one can state that the diagonal riders provided the largest contribution of bending stiffness to the model. This assertion is supported by the deflection data shown in Figure 19. The removal of diagonal riders resulted in the largest relative increase in model deflection compared to the relative deflection increase produced by the removal of other structural components.

The bending stiffness of the structural components used in the model tests are scaled stiffnesses. Consequently, in order to estimate the effect of the components on the actual ship, the bending stiffness of the actual ship was determined and appropriately scaled. Since the maximum bending moment of the ship occurs at Station 10, the bending stiffness of the ship at Station 10, as reported in Reference 3, was scaled according to scaling rules derived in Reference 11.

The effect of the structural components on the actual ship were determined by adding the bending stiffness of each component to the scaled bending stiffness of the ship. The resulting bending stiffness was assumed to represent the bending stiffness of the ship as if the components were installed in the ship. Therefore, the relative contribution of the components to increasing

the bending stiffness of the ship was determined and is shown in Figure 21. Note that the contributions of the members to increasing the bending stiffness of the ship are significantly smaller than their contribution to increasing the bending stiffness of the model. This discrepancy is due to the low bending stiffness of the scale model in comparison to the scaled bending stiffness of the ship.

The results of a bending analysis of the test data estimated an 6.5% increase in the ship's bending stiffness due to three sets of diagonal riders. Note that the analysis employed many simplifying assumptions. The actual increase in ship stiffness provided by the diagonal riders may differ and can only be determined with confidence by instrumenting the ship prior to lift-off from the keel blocks.

SUMMARY

A study of the addition of diagonal riders to the USS CONSTITUTION has been completed. The goals of the study were to estimate any hogging rate reduction produced by the riders and to develop an improved understanding of the mechanisms that cause hogging in wooden ships. Since hog is caused predominately by bending loads, the effect of the riders on the bending response of the ship was investigated and both analytical and experimental methods were employed. Within the scope and assumptions made in the study, the riders were found to have little effect on the bending response of the CONSTITUTION.

Deformation of pinned connections contributes to the progression of hog in a wooden ship. This deformation is due to bearing stresses, pin deformation and pin corrosion. The riders may contribute to reducing the hogging rate of the CONSTITUTION, particularly in the short

term, by virtue of the tightly fastened joints between the riders and the hull. The analytical and experimental evaluations of the proposed riders, however, did not account for these effects. Consequently, the exact effect of the riders on the ship will only be determined if they are installed, key structural components of the ship are instrumented, and the ship is set afloat.

RECOMMENDATIONS

An improved weight survey of the ship must be completed. Balancing the weight curve with the buoyancy curve will provide the long-term benefit of reducing the rate of hogging in the ship. Redistribution of weights on the ship, as practical as possible, will reduce the bending moment experienced by the hull which causes both the primary bending and secondary shear deflections.

The following monitoring techniques are suggested with long term preservation of the ship in mind. A system which will monitor the deformation of critical structural members is recommended to be installed prior to lift-off of the ship from the keel blocks. The keel, keelson, sister keelson, diagonal riders, and the new knees which join the riders to the hull must be instrumented. For short-term data acquisition, strain gaging of critical structural members is recommended. Strain gages will monitor forces induced in the ship due to lift-off as well as check the adequacy of the new weight balance. The data would also be used to monitor any adverse loading induced in the new or existing structure. The CONSTITUTION has never been formally instrumented during lift-off and the data gathered would be valuable from a structural as well as historic viewpoint.

Strain gages are short-term monitoring devices since long-term environmental exposure

may degrade their performance. Consequently, a long-term monitoring system for the ship must be devised. A possible system would utilize visual systems such vernier plates and/or transit surveying equipment. A vernier plate system would consist of plates with calibrated distance markings on their edges similar to a ruler. Plates would be affixed to hull planking so that the relative horizontal movement between planking could be easily assessed. In addition, transit survey equipment would be used to sight multiple benchmarks based on a strategy of previously recorded hull movements. The ship already has these benchmarks and additional ones would enhance this current method.

Both the short-term and long-term monitoring systems, whether applied individually or in concert will provide an improved understanding of the ship's current condition as well as physical data to aid in planning for long-term preservation.

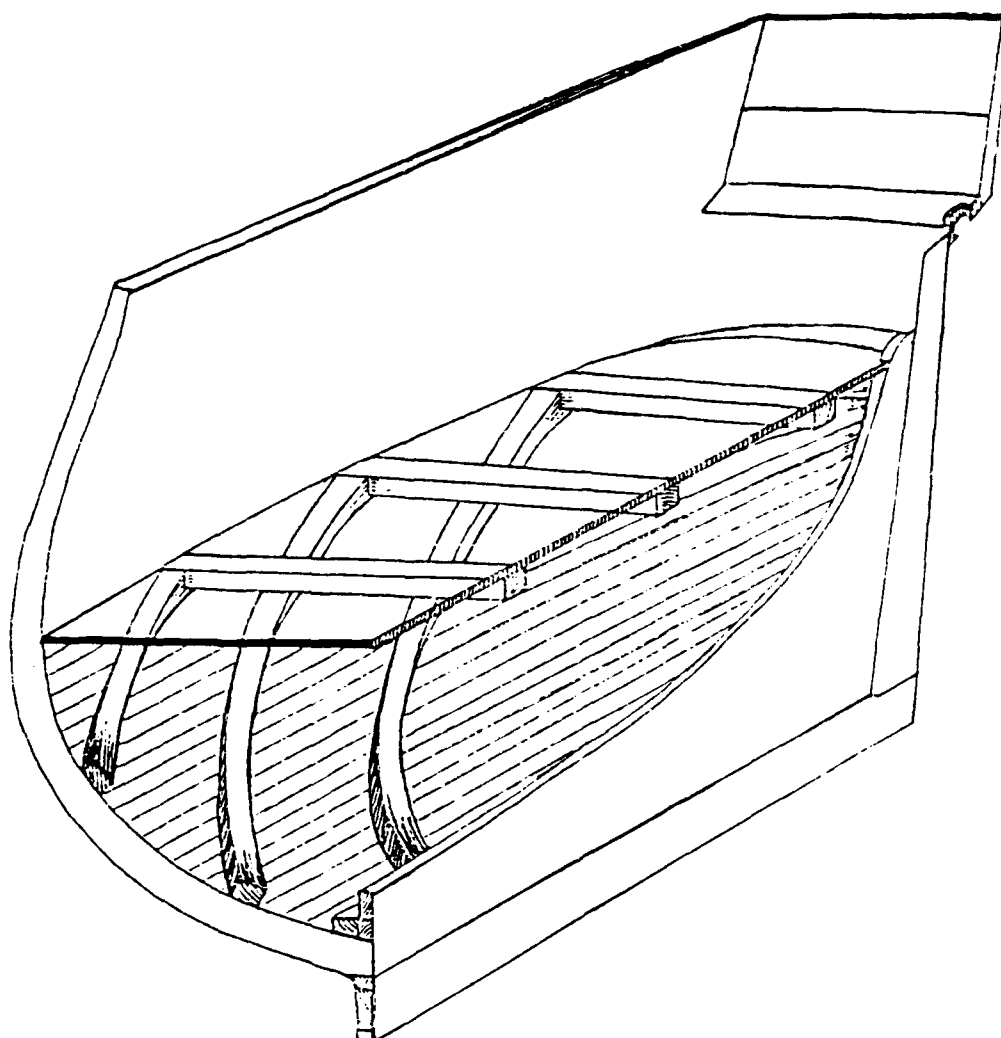


Fig. 1. Schematic drawing of proposed riders

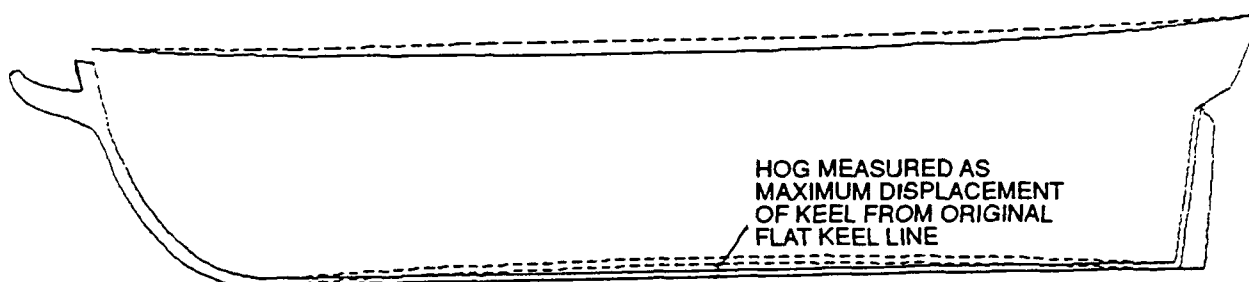


Fig. 2. Location of hog measurement

Vertical versus Horizontal Stack Movement

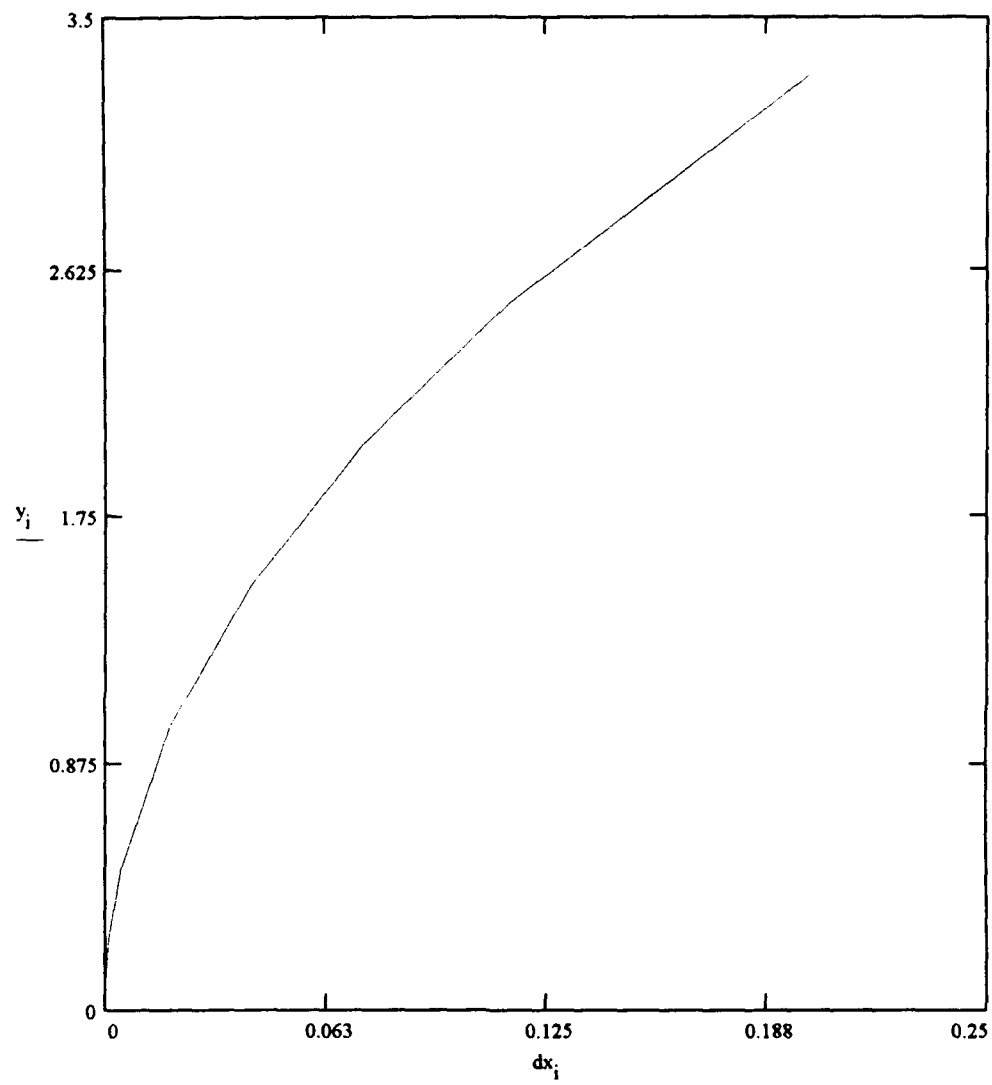


Fig. 3. Relationship between vertical and horizontal movement

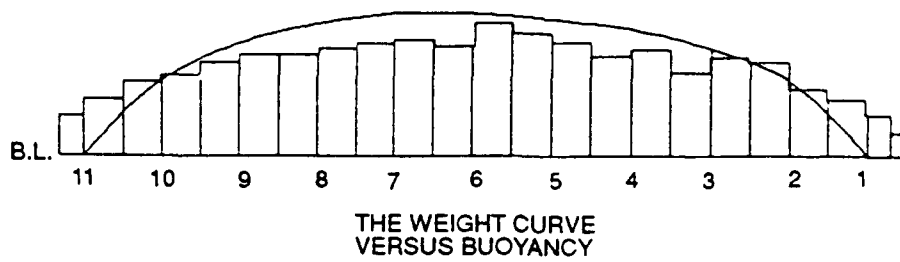


Fig. 4. Typical weight and buoyancy distributions

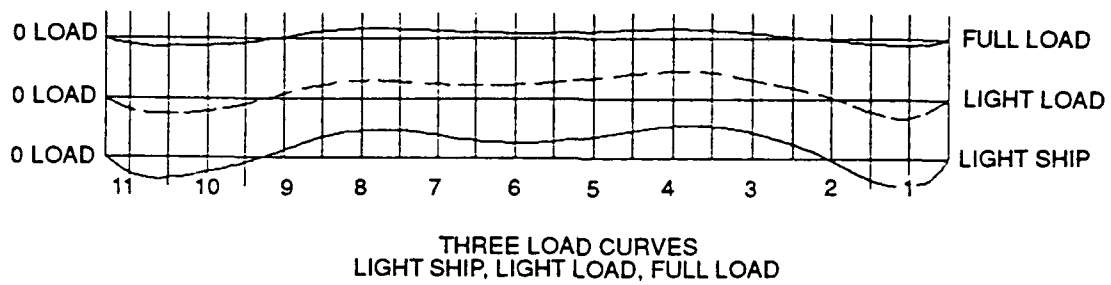


Fig. 5. Typical load distributions

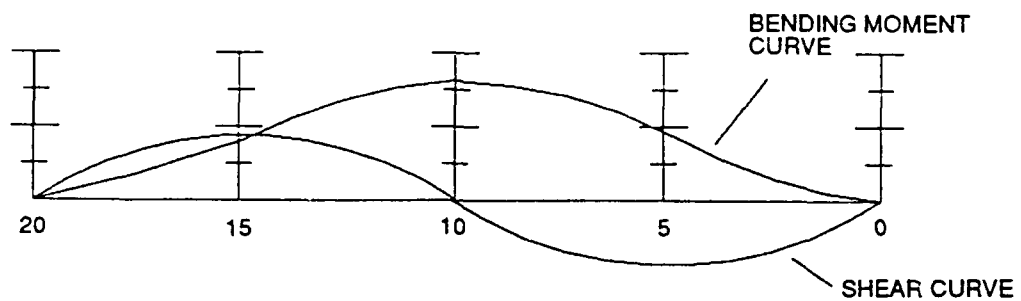
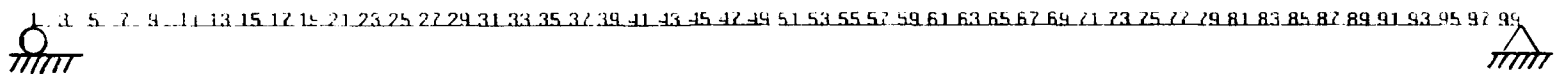


Fig. 6. Typical bending moment and shear distributions

NOTE: EVEN ELEMENT LABELS OMITTED FOR CLARITY



y

x _____ z

Fig. 7. ABAQUS beam representation of USS CONSTITUTION

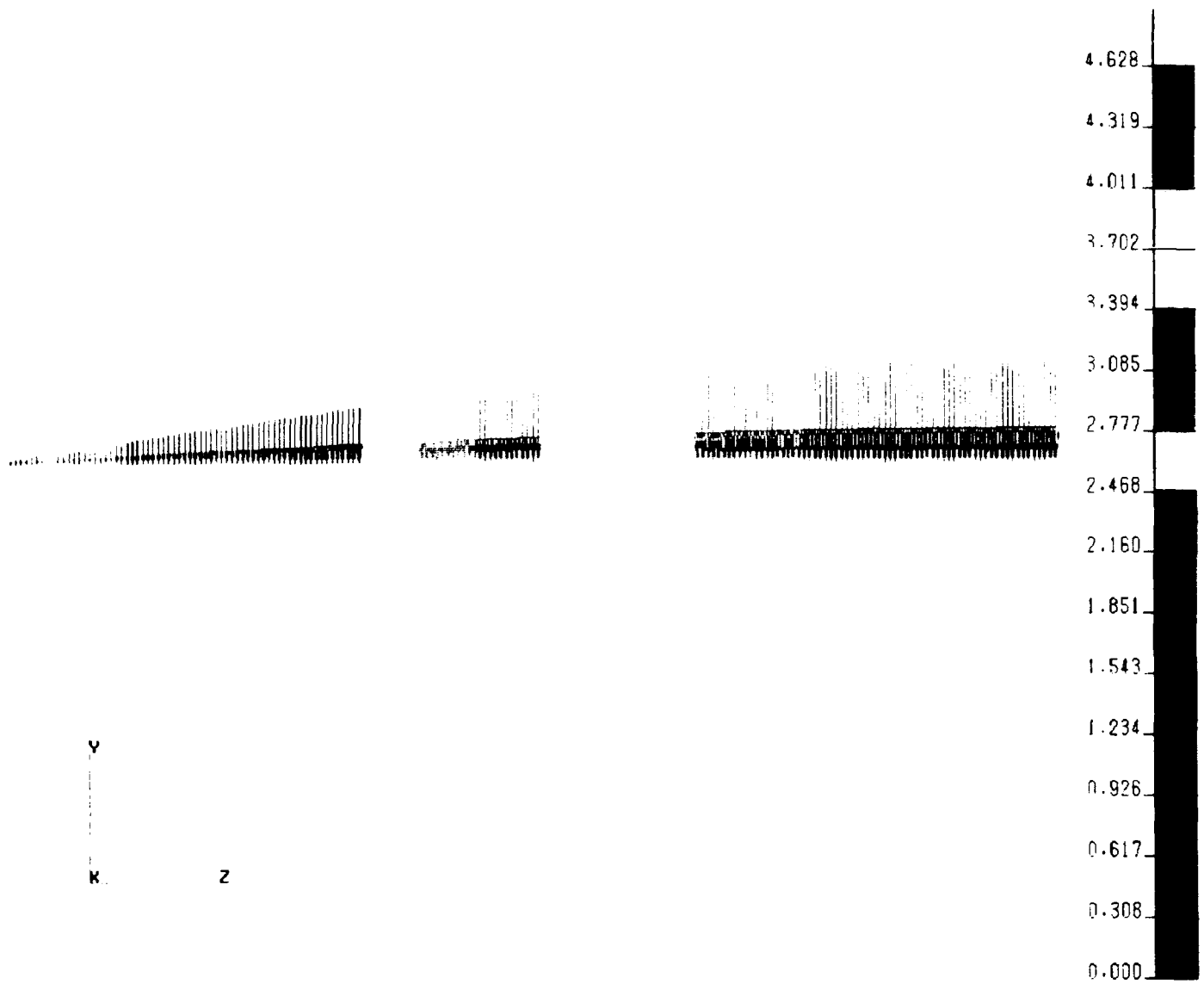


Fig. 8. CONSTITUTION vertical deflection - ABAQUS beam analysis

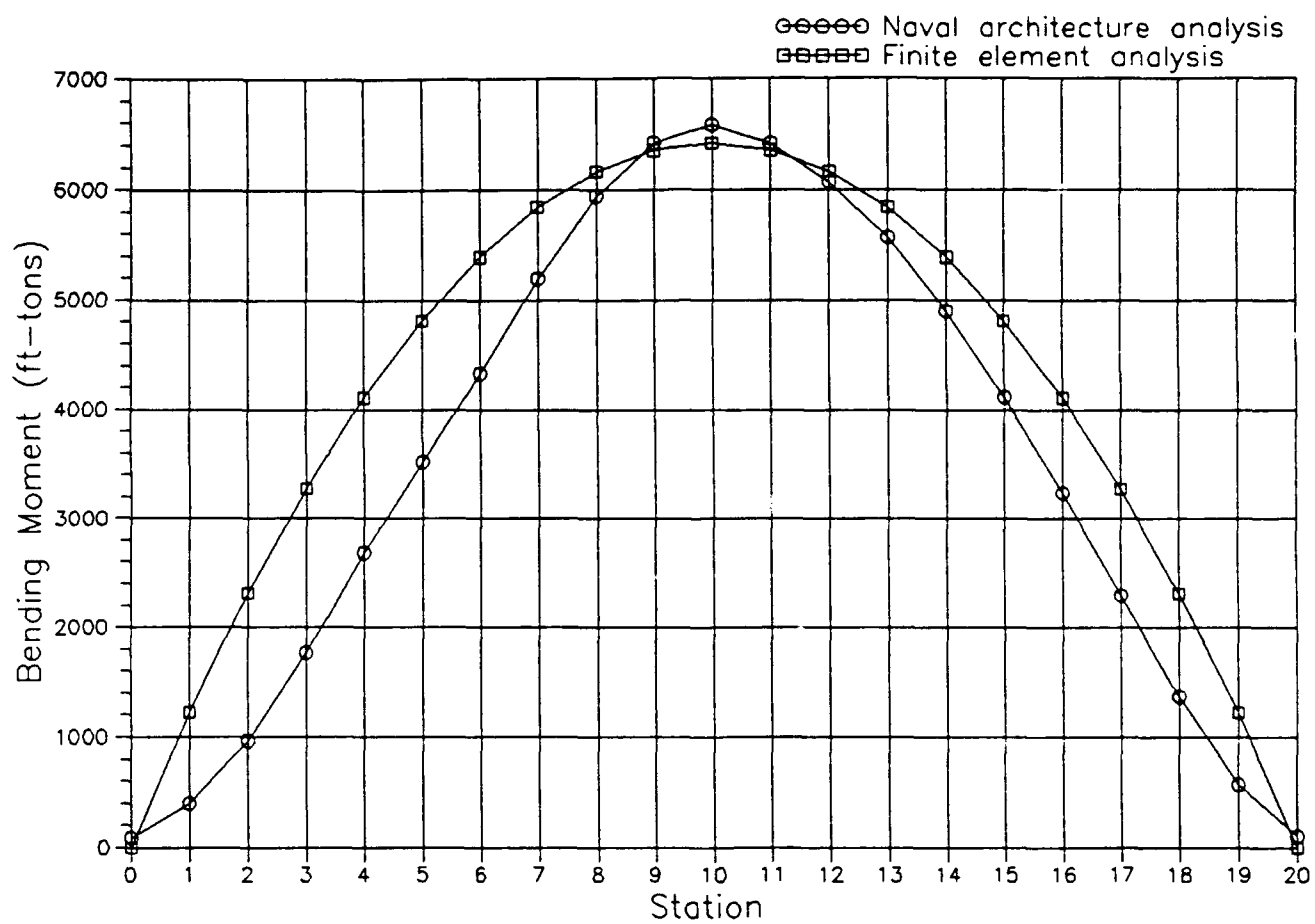


Fig. 9. Predicted longitudinal bending moments for USS CONSTITUTION

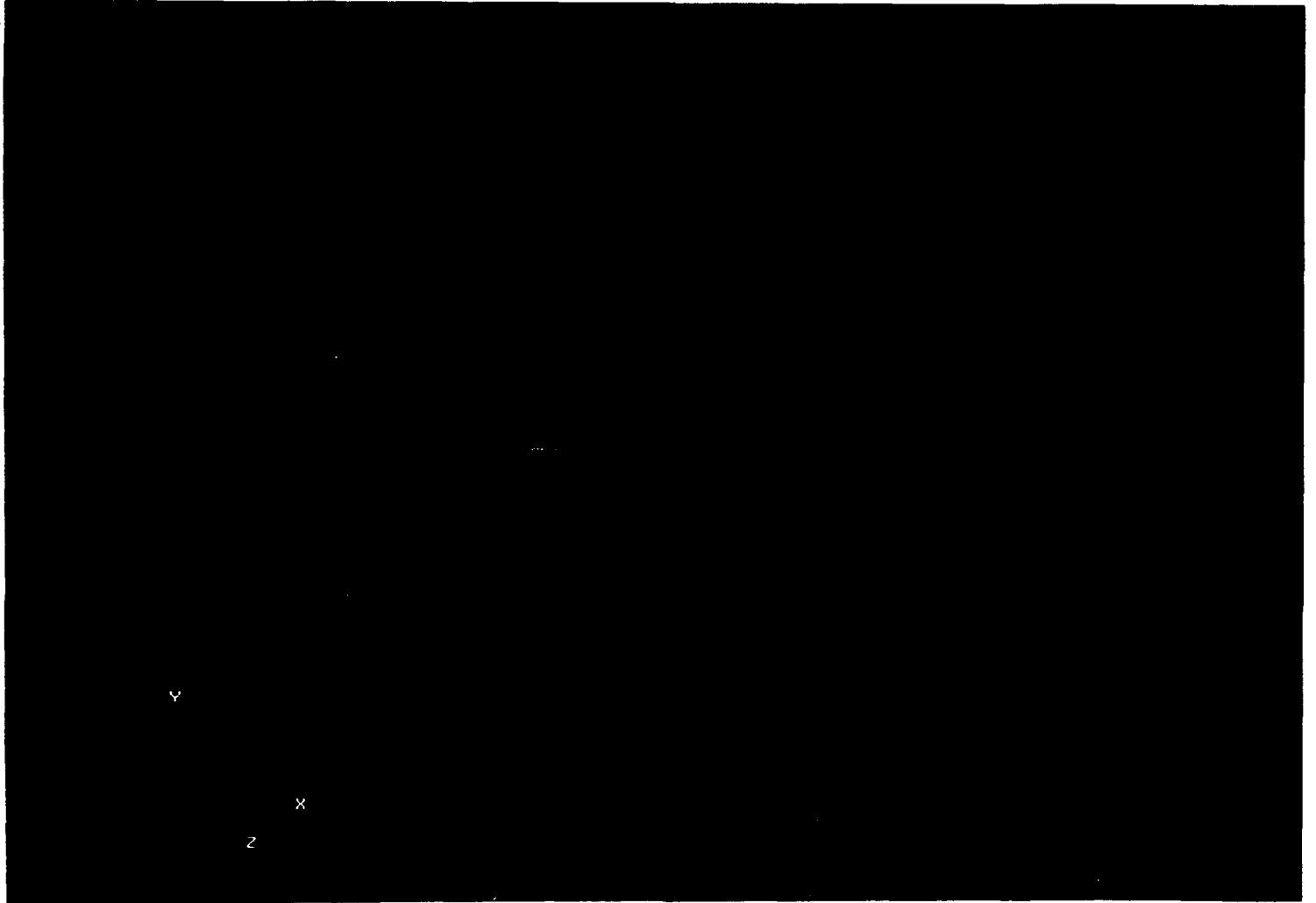


Fig. 10. Notional hull geometry

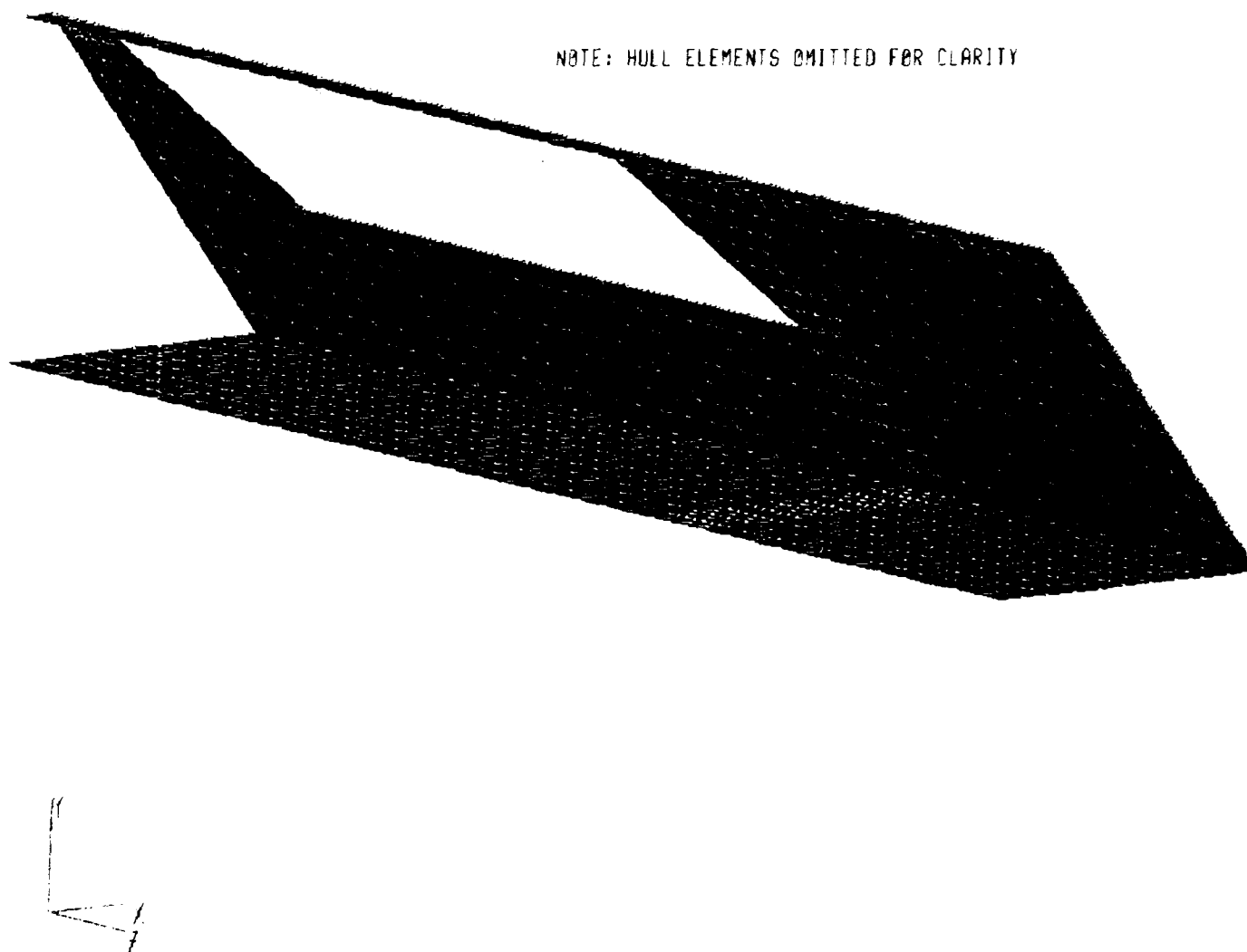


Fig. 11. ABAQUS representation of stiffened notional hull

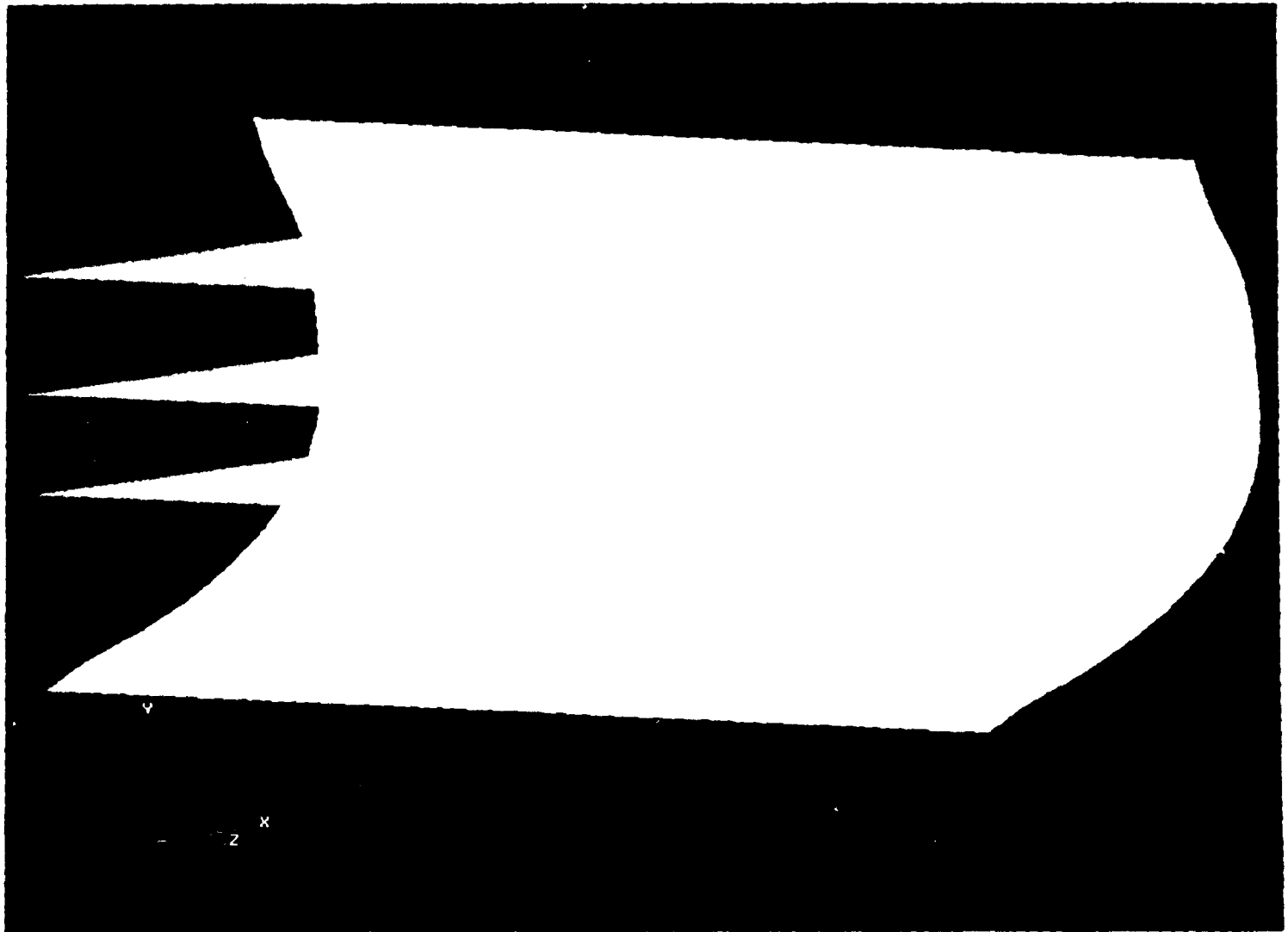


Fig. 12. Improved geometric representation of USS CONSTITUTION

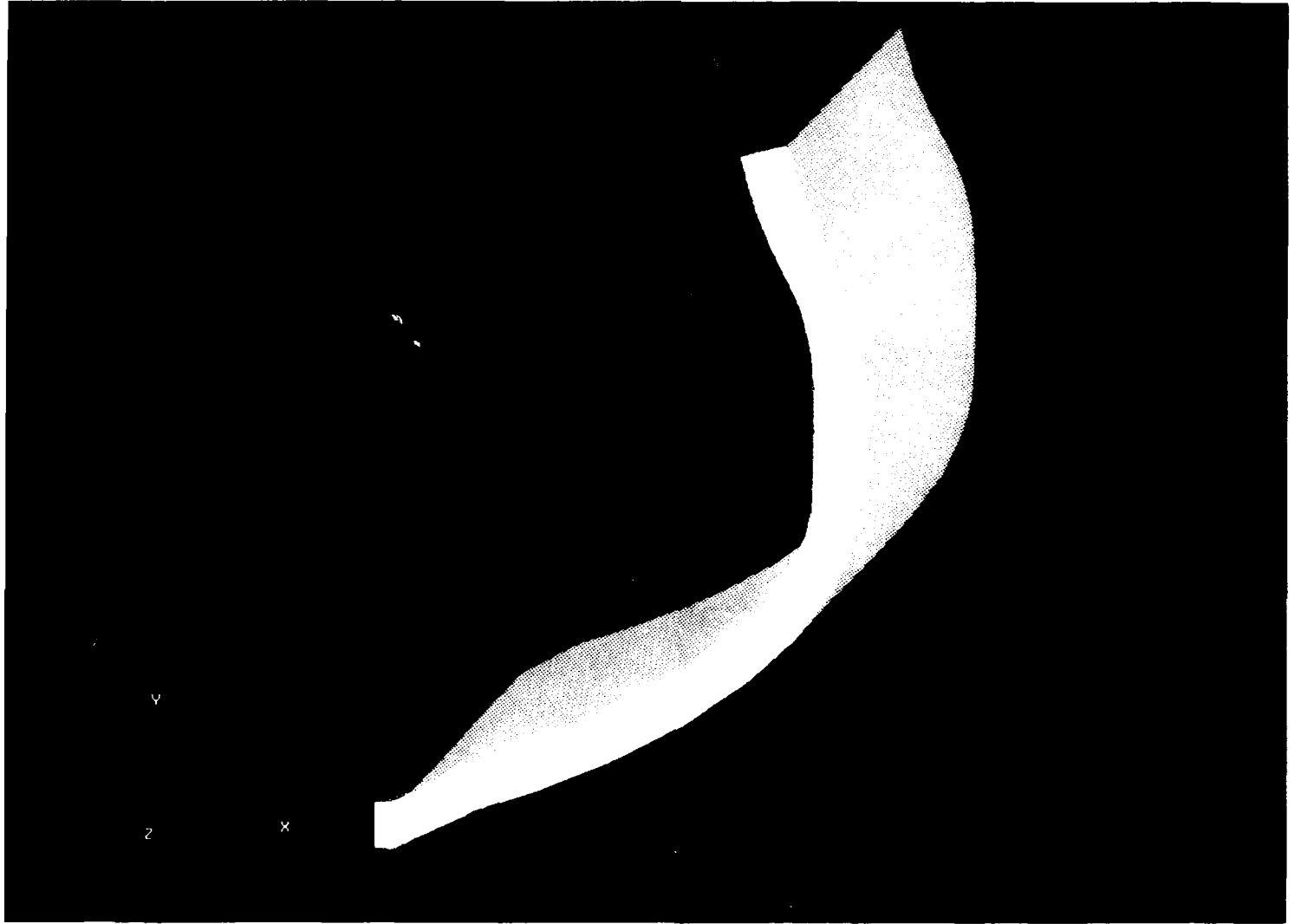


Fig. 13. Solid hull geometric representation

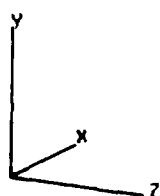
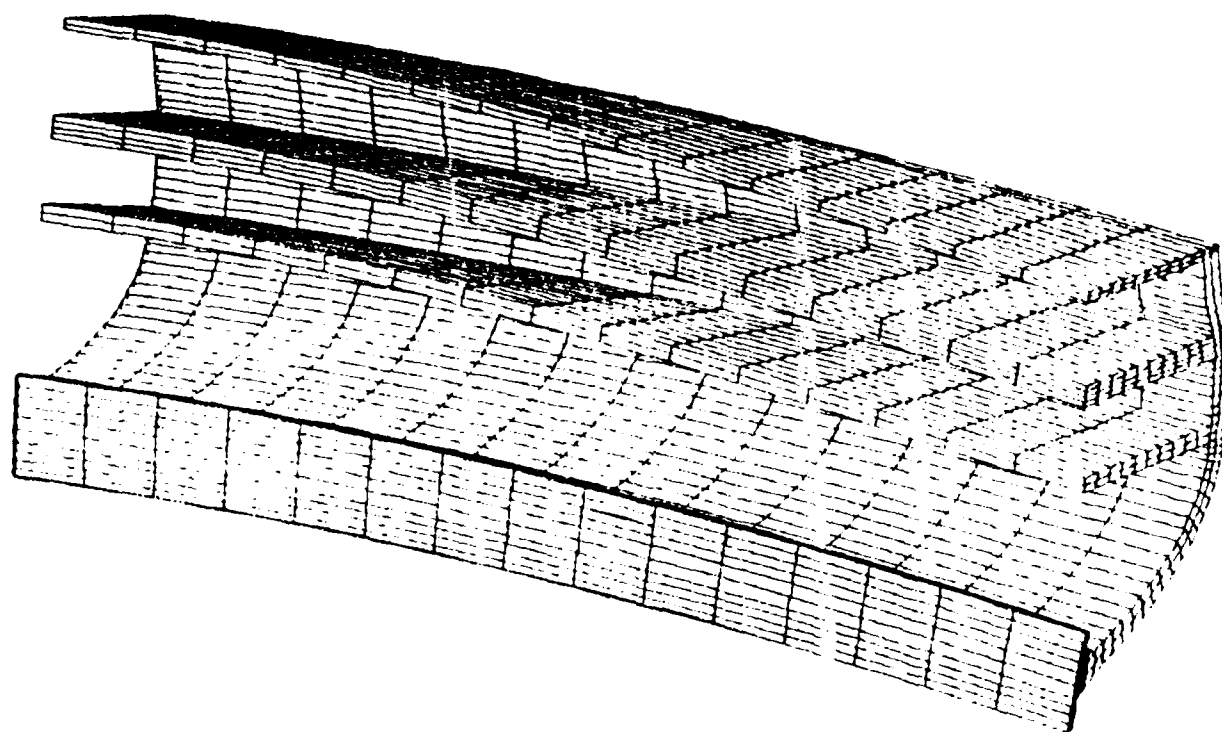


Fig. 14. Deformation of solid hull representation

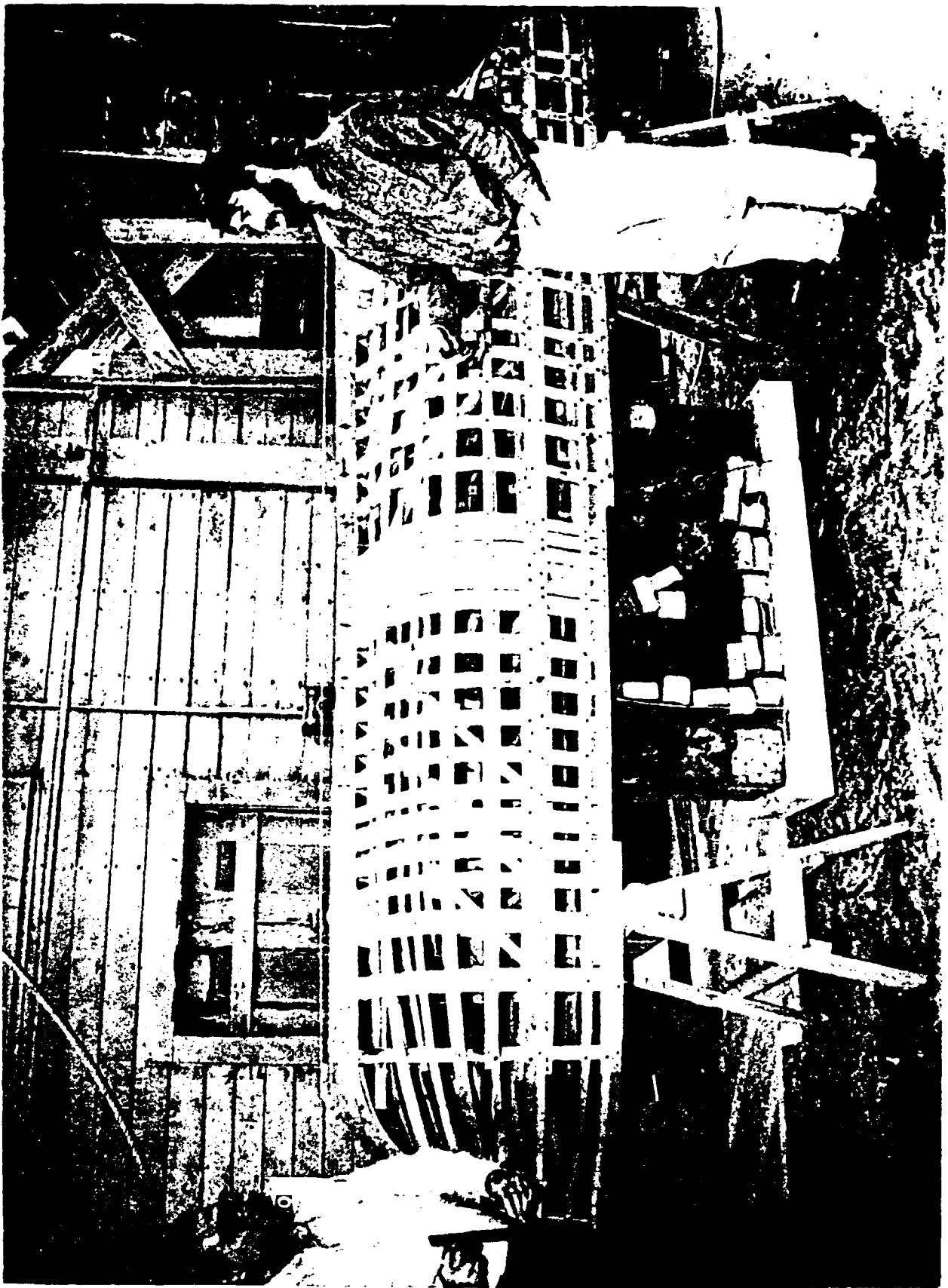


Fig. 15. Scale model configured for loading



Fig. 16. Keel reference line



Fig. 17. Scale model with all proposed structural components installed

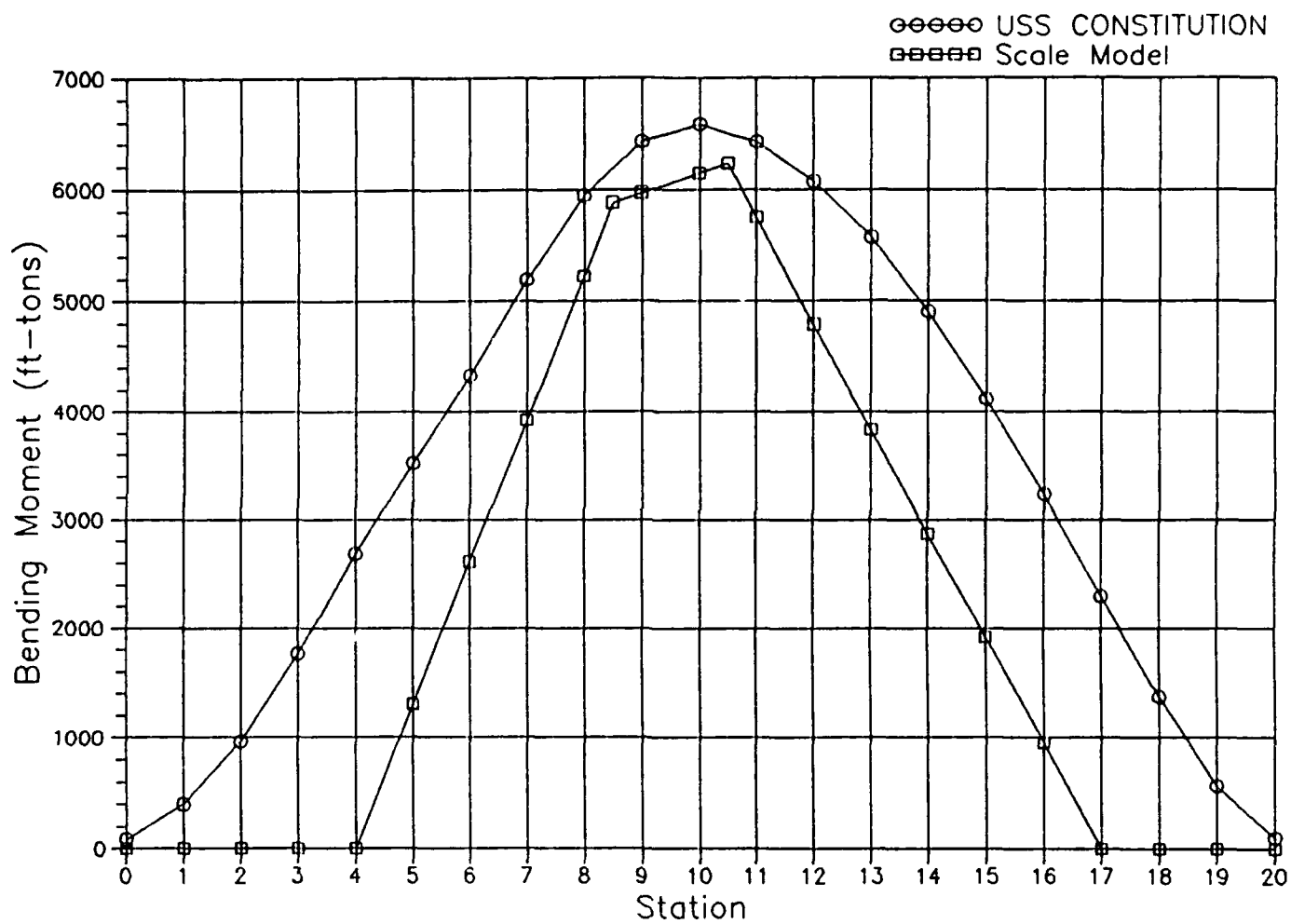


Fig. 18. Longitudinal bending moments for USS CONSTITUTION and scale model

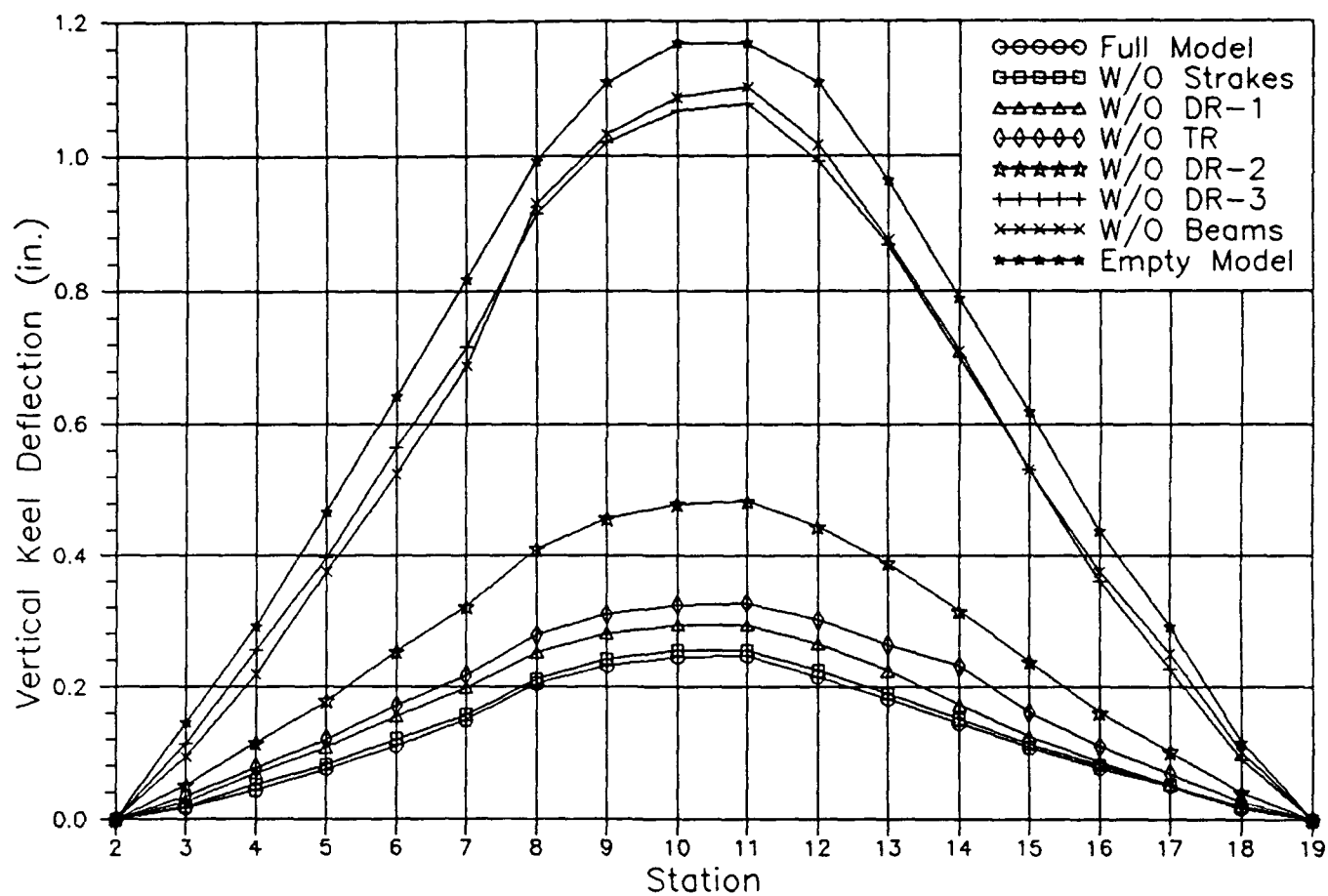


Fig. 19. Keel deflections for eight scale model structural configurations

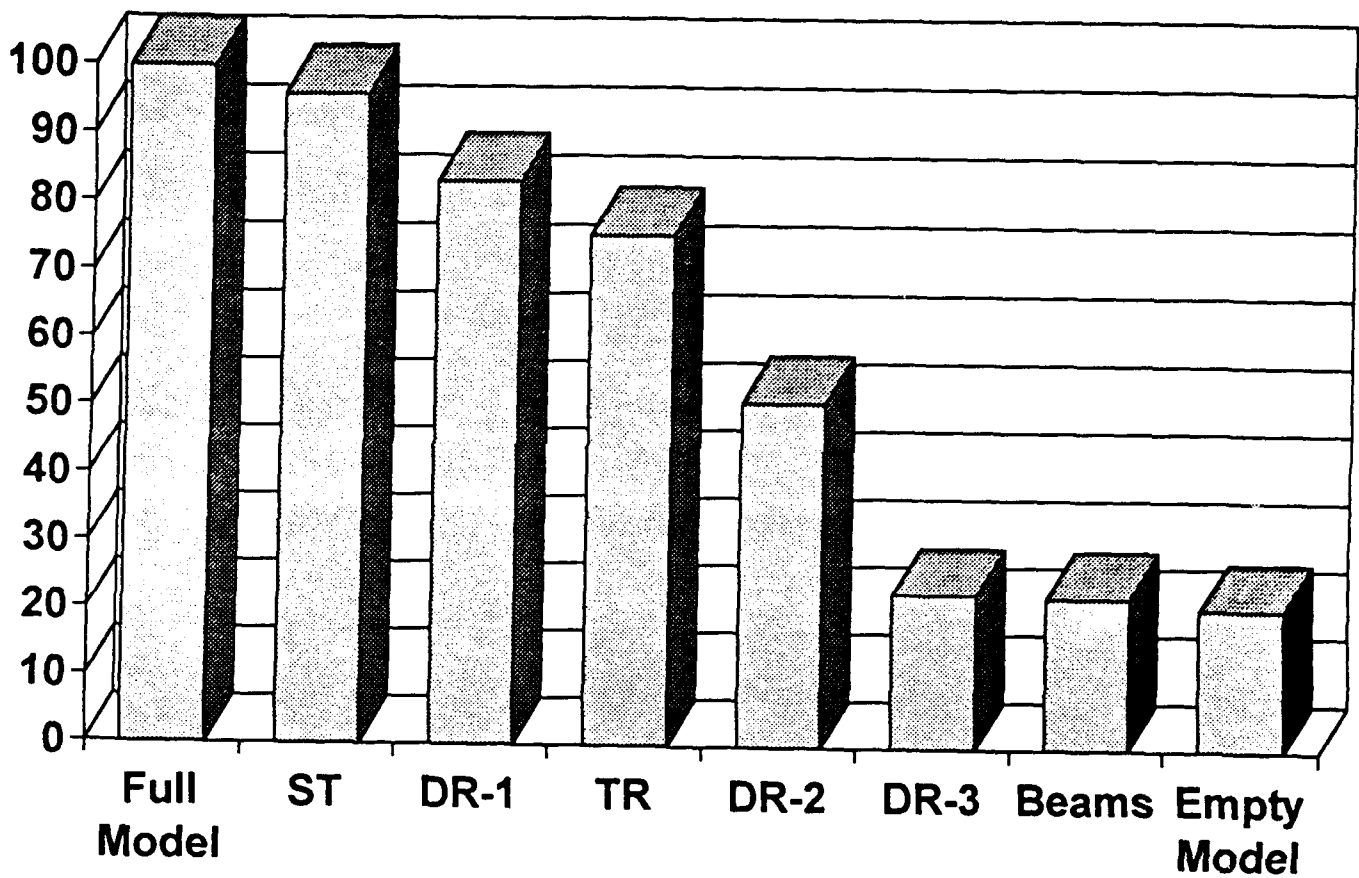


Fig. 20. Percent decrease in scale model bending stiffness due to the removal of proposed structural components

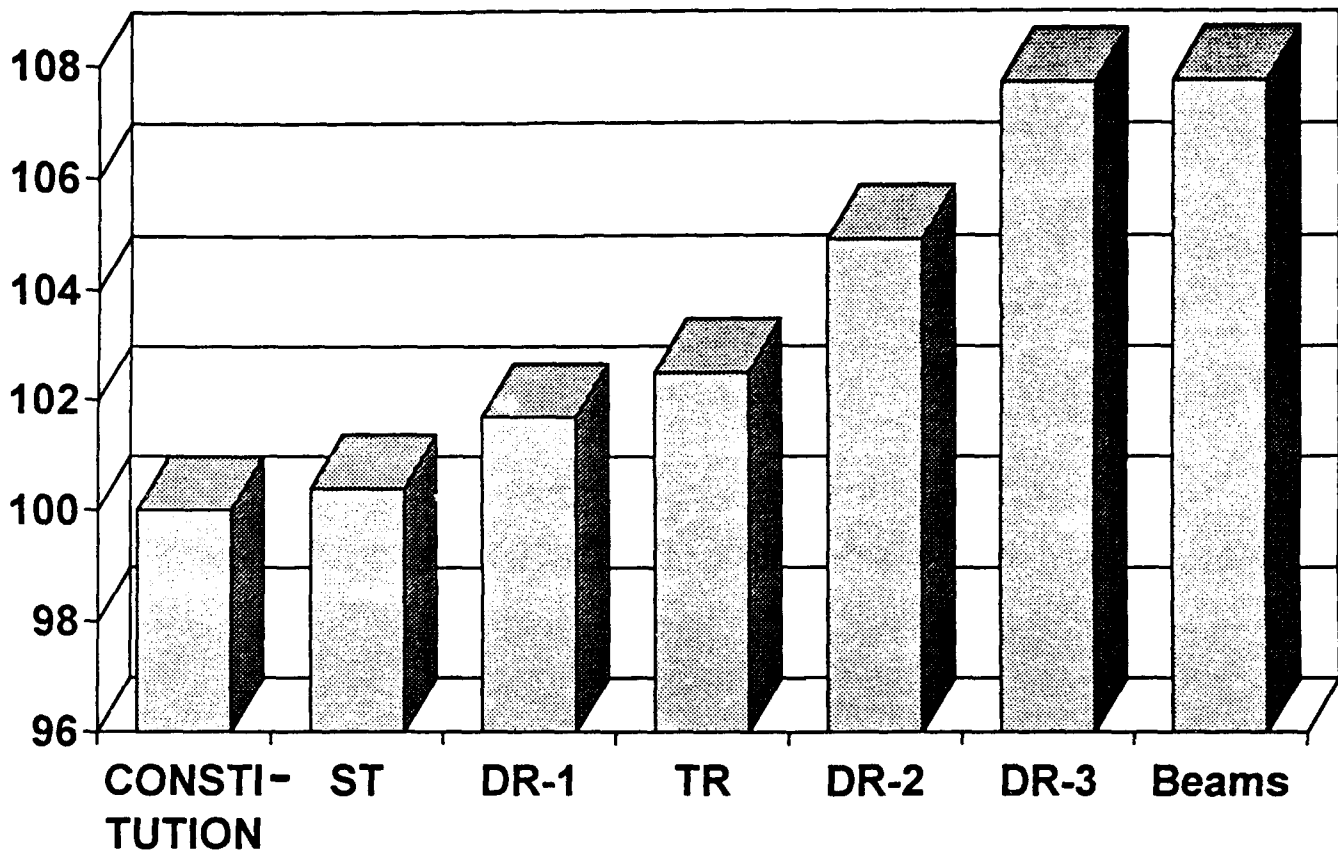


Fig. 21. Percent increase in USS CONSTITUTION'S bending stiffness due to installation of proposed structural components

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